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Sources of Asian dust and role of climate change versus desertification in Asian dust emission

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[1] Simulations of Asian dust emissions over the past 43 years are presented based on a size-dependent soil dust emission and transport model (NARCM) along with supporting data from a network of surface stations. The deserts in Mongolia and in western and northern China (mainly the Taklimakan and Badain Juran, respectively) contribute ~70% of the total dust emissions; non-Chinese sources account for ~40% of this. Several areas, especially the Onqin Daga sandy land, Horqin sandy land, and Mu Us Desert, have increased in dust emissions over the past 20 years, but efforts to reduce desertification in these areas may have little effect on Asian dust emission amount because these are not key sources. The model simulations indicate that meteorology and climate have had a greater influence on the Asian dust emissions and associated Asian dust storm occurrences than desertification. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 1610 Global Change: Atmosphere (0315, 0325); 9320 Information Related to Geographic Region: Asia. **Citation:** Zhang, X. Y., S. L. Gong, T. L. Zhao, R. Arimoto, Y. Q. Wang, and Z. J. Zhou, Sources of Asian dust and role of climate change versus desertification in Asian dust emission, *Geophys. Res. Lett.*, *30*(24), 2272, doi:10.1029/2003GL018206, 2003.

1. Introduction and Motivation

[2] Sand and dust storms are widespread natural phenomena. Heavy dust storms disrupt human activities, and over the past few decades it has become apparent that the long-range transport of dust links the biogeochemical cycles of land, atmosphere and ocean [*Bergametti*, 1998; *Martin and Gordon*, 1988], possibly even influencing the global carbon cycle [*Ridgwell*, 2002], and having a significant effects on regional radiative balances [*Kinne and Pueschel*, 2001; *Sokolik and Toon*, 1996; *Sokolik et al.*, 2001]. A geochemically significant quantity of Asian dust, estimated to be 400–500 Tg [*GESAMP*, 1989], is deposited in the North Pacific each year. Approximately 240 Tg of the dust is re-deposited in Chinese deserts each year [*Zhang et al.*, 1997], 140 Tg falls out over other parts of China [*Zhang et al.*, 1997], and the dust can also transport from Gobi desert as far as Europe [*Grousset et al.*, 2003], showing the global nature of these effects.

[3] In addition to the natural dust production, human activities have created another potential source for dust through the process known as desertification, but the contribution of desertification by human activities to global dust emission is still open debate with the estimation varying from 50% [*Tegen et al.*, 1996] to un-significant values [*Ginoux et al.*, 2001; *Prospero et al.*, 2002]. Soil dust from Asia is at times a major component of the tropospheric aerosol in mid-latitude regions, and while the expansion of deserts caused by human activities can increase dust fluxes (Figure 1), the magnitude of this effect is not well constrained.

[4] Information on the distribution of Asian dust sources and the quantity of dust produced is needed to quantify the effects of dust on climate, but pinpointing dust sources and more accurate figures regarding source strengths also is crucial for evaluating the relative influences of desertification versus climate change on dust fluxes. The analysis of dust storm frequencies is one of more commonly used approaches to identifying dust sources [*Middleton et al.*, 1986; *Natsagdorj et al.*, 2003]. The visibility-based approach is only semi-quantitative indicator, however, because the frequencies of dust storms do not necessarily capture the strength of dust storms. That is, beyond the threshold criteria for reporting an event, the quantities of dust raised vary from storm-to-storm, and a region with less frequent but more severe dust storms may be a stronger source than areas with more frequent but weaker ones. Observer bias is an intrinsic limitation of the visibility approach. Furthermore, there is not necessarily a direct correspondence between dust storm frequencies and dust sources because dust transported into the region-as opposed to newly raised dust-also can reduce visibility.

[5] Numerical modeling provides a systematic approach for identifying and evaluating dust source regions [e.g., *Shao*, 2001]. These numerical methods are crucially dependent on parameterizations of dust deflation, and as such require accurate information on the geographical distributions of the deserts, their surface roughness elements, grain size, soil moisture, etc. [*Marticorena and Bergametti*, 1995]. Validation of model simulations is a key issue in these studies.

[6] Here we use the Northern Aerosol Regional Climate Model (NARCM) to simulate the Asian dust emissions from 1960 to 2002. Prior comparisons between model output and network observation during the ACE-Asia Experiment (the

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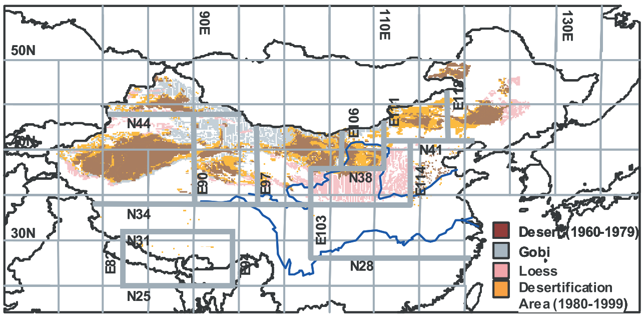

Figure 1. Chinese desert distributions during 1960s to 70s and desert plus desertification areas during 1980s and 90s.

Asian Pacific Regional Aerosol Characterization Experiment) have shown the model reproduces with reasonable accuracy the dust emission strength and hence the soil dust concentrations in China and areas downwind the source regions [*Gong et al.*, 2003; *Zhang et al.*, 2003a, 2003b; *Zhao et al.*, 2003]. The model was driven by the NCEP re-analyzed meteorology, and was run on a polar stereographic projection with a horizontal resolution of 100 × 100 km and 22 vertical levels on a Gal-Chen terrain-following coordinate system from the ground to 30 km. The model is restricted to the suspension of particles <40 μm because they are most readily transported by turbulent eddies and advection. Twelve dust particle-size classes from diameters of 0.01 to 41 μm were used to represent the size distribution of soil dust. The dust fluxes and concentrations were calculated for each size bin. The model domain covered East Asia, the North Pacific and western North America.

[7] A soil texture map for China was generated to drive the particle-size specific soil dust emission scheme [*Alfaro et al.*, 1997; *Marticorena and Bergametti*, 1995]. Surface observations of the size-distribution of dust aerosol during local dust storm conditions at nine Chinese desert regions [*Zhang et al.*, 2003b] were used to constrain the size distribution of vertical dust flux. Information taken from Chinese desert maps from 1960s to 70s was used to generate the distribution of deserts, gobi, sandy lands, loess and other land types prior to 1980. This information was mainly obtained from the aviation images and surveys conducted from the 1950s to the 70s [*Wang*, 1995]. In contrast, the maps of desert and expanded deserts and sand areas for the 1980s to 1990s, were mainly based on surveys and satellite images [*CAS*, 1998] (see Figure 1).

2. Locations and Source Strengths for Asian Dust Sources

[8] The simulated springtime dust emissions over the past 43-years indicate that Asian dust mainly originates from 10 source areas (Figure 2). Several of the dust sources lie beyond Chinese borders, especially Source S1, S2 and some parts of S10, and on average these contribute ~40% of the total springtime Asian dust. The combined dust produced in Mongolia (S2), the deserts in western China, including the Taklimakan Desert (S4) and the high dust emission areas in northern China, containing the Badain Jaran Desert, Tengger Desert and Ulan Buh Desert (S6) amounts to ~70% of the total dust production. These three areas (S2, S4, and S6) are the major sources for Asian dust aerosol.

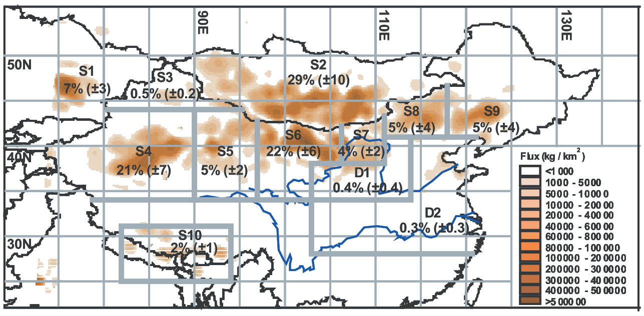

Figure 2. Sources (S1 to S10) and typical depositional areas (D1 and D2) for Asian dust indicated by spring average dust emission flux (kg km^{-2} 3 months^{-1}) between 1960–2002. The percentages with standard deviation in the parenthesis denote the average amount of dust production in each source and depositional areas of the total mean of emission amount in the last 43 yrs.

[9] Dust from S1 (including deserts and sands in Kazakhstan), S5 (containing the desert in Tsaidam Basin and the Kumutage Desert), S7 (mainly composing Mu Us Desert and Hobq Desert), Onqin Daga sandy land (S8) and Horqin sandy land (S9), each contribute 4% to 7% of the total emission (Figure 2). Minor contributions can also be found from S3 (including Gurbantunggut Desert, 0.5%) and source areas in south of the Tibetan Plateau (S10, 2%). The historical dust depositional areas (D1 and D2) and some sandy coastal areas also eject small amounts of the dust.

3. Role of Climate Change Versus Desertification in Asian Dust Emission

[10] Time series of total dust emissions from the various source areas differ for March, April and May over the last 43-yrs, but the trend for April (~40% of the springtime emissions) is similar to that for the springtime emission and for the yearly dust frequencies recorded at the Chinese

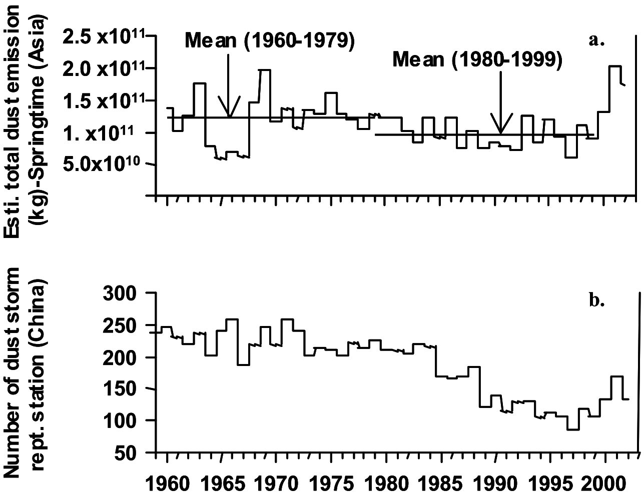

Figure 3. Time series of the estimated total dust emission (kg) in springtime for whole investigated areas sine the last 43-yrs (a), and the station number of dust storm report in China (b) at the same period.

Meteorological Administration stations (Figure 3). This agreement affirms the major contribution of Chinese sources to Asian dust and attests to the overall reliability of the model results. Some inconsistencies between approaches are to be expected due to differences between the quantitative (model simulations) versus semi-quantitative (dust storm reports) nature of the data; the fact that the simulations were for spring whereas the dust storm frequencies are reported on an annual basis; and differences in the areas considered, that is the dust storm reports were for China only compared with the model simulations which included regions outside of China.

[11] After a trend of increasing Asian dust emissions from 1961 to 1963, followed by a low emission period from 1964 to 1967, the model simulations indicate that amount of dust produced generally decreased after 1969. Note that the simulated dust fluxes often switch from high to low emission after intervals of 3 to 4 yr (Figure 3a). It is also noteworthy that no abrupt change in the pattern of emissions was observed in 1979 to 1981 which is when the data inputs to the model changed. The most recent simulations showed dust emission began a two-year rise from 2000 to 2001, reaching the highest of the 43-yrs in 2001 then dropped again in 2002. The average springtime dust emission for particles less than 40 μm diameter from 1960 to 1979 ($\sim 1.2 \times 10^{11}$ kg) was ~24% higher than during 1980 to 1999 ($\sim 0.97 \times 10^{11}$ kg). According to our model simulations, the dominant meteorological factors that control the dust emission flux are surface wind speed and precipitation. The later controls the soil moisture contents.

[12] The observed trends and relative lower dust level in 1980 to 1999 suggest that climate change has been a more important determinant of dust emissions than the expansion of desert lands due to desertification. Over the past 43 years, the area of China occupied by deserts increased ~2%[*Zhong*, 1999] to 7%[*Zhu and Zhu*, 1999] in average (Figure 1), and if desertification were the predominant influence on dust production, the emissions and dust storm reports would have followed an increasing trend, and the averaged emission during 1980 to 1999 would have had a higher value than that during 1960 to 1979. The large increase in dust and sand storms over the past three years (Figure 3) is more logically explained by changes in weather and climate than desertification because the land area affected by desertification changes relatively little over a few years time [*Zhong*, 1999]. Thus two lines of evidence indicate that meteorological factors and climate change have been more important than desertification with respect to a decreasing occurrence of the Asian dust storms.

[13] The encroachment of China's deserts occurs mainly at the rim of the Onqin Daga sandy land, the southwestern and northwestern fringes of the Horqin sandy land, the central and northern parts of Mu Us Desert; and to some degree in the desert in Qaidam Basin, the Kumutage Desert, and in the eastern part of Badain Jaran Desert (Figure 1). There were minor expansions in the area extent of sand lands at the margins of Taklimakan and Gurbantunggut Desert and other areas of China. The model calculations indicated that there was an increase in the 5-yr averaged dust emissions relative to 40-yr average over the past 20 years (Figure 4) at the Onqin Daga sandy land (S8), Horqin sandy land (S9), and to some degree in the Mu Us Desert (S7) and Kumutage Desert (S5); these increases can be attributed to desert expansion. On the other hand, the amounts of dust ejected from the three major sources, Mongolia (S2), Taklimakan (S4) and Badain Jaran Deserts (S6), and from sources in the Gurbantunggut (S3) and Kazakhstan (S1), exhibited an decreasing trend over the last 20-yrs (Figure 4), and it was the changes in dust emissions from these regions that were largely responsible for the overall trends shown in Figure 3.

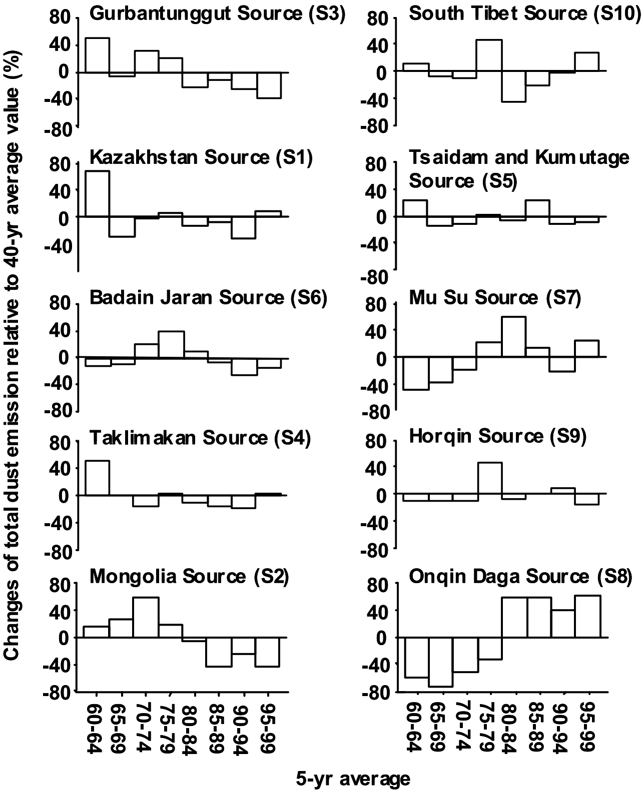

Figure 4. Variations in 5-yr averaged total dust emissions relative to 40-yr mean between 1960–1999 at each source regions.

4. Conclusions and Questions Remaining

[14] On the basis of the NARCM model simulations the sources in Mongolia (S2), Taklimakan (S4) and Badain Jaran (S6) produce 29%, 21% and 22% of the Asian dust, respectively. Five sources, including those in Kazakhstan (S1), the desert in the Qaidam Basin and Kumutage Desert (S5), Mu Us Desert (S7), Onqin Daga sandy land (S8), and the Horqin sandy land (S9) each produce few percent of the dust. The regions south of Tibet (S10) and the Gurbantunggut Desert (S3) are minor sources, combining for less than 3% of the dust production.

[15] Changes in the amounts of Asian dust and associated dust storm occurrences over the past few decades apparently are driven mainly by weather and climate, but the simulations do show some impact of dust originating from some desertified areas. Therefore there is the potential for ecological measures and changes in land use practices to reduce dust emissions and the occurrence of dust storms. Unfortunately, the "anthropogenic sources" including those mainly

from the Onqin Daga sandy land (S8), Horqin sandy land (S9), Mu Us Desert (S7), even the deserts in the Qaidam basin and the Kumutage Desert (S5), which have been the targets of dust control measures, are not major dust producers. Nevertheless, it is also possible that some desertified regions, in particular areas with 200–400 mm of annual precipitation, could resume their original appearance as arid steppes. As for the possible transport influence of dust on China's big cities after, a detailed study is under way to include the development of measures to rehabilitate of some desertified lands.

[16] Numerous questions remain concerning dust fluxes that can be evaluated using approaches similar to those used here; these questions include: What's the critical climatic index for dust emission? What's kind of mechanism of climate impact on the dust emission and transport? What changes in climate, especially in 1970s and 1990s and in the last three years were responsible for the changes in dust emissions? All these topics should be addressed in future studies.

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